Black Holes at the LHC :on and off the brane

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IPMU workshop, Dec.18 2007

Rotating Black Holes at future colliders

I: Greybody factors for brane fields

D. Ida, K.-y. Oda, SCP, **Phys.Rev.D67:064025,2003, Erratum-ibid.D69:049901,2004.**

II: Anisotropic scalar field emission

D. Ida, K.-y. Oda, SCP, **Phys.Rev.D71:124039,2005.**

III: Determination of black hole evolution

D. Ida, K.-y. Oda, SCP, **Phys.Rev.D73:124022,2006.**

IV: Case with bulk Standard Model fields

Hopefully Coming soon

Goal of this talk is as follows.

- In this talk, I just try to summarize the current status of bh studies (include some new things in RS1+the bulk SM)
- Try to give you brief ideas about BH production mechanism.
- Try to tell you how we can calculate `black hole signals' via Hawking radiation where you need to know 'greybody factors'.
- Try to call for your attention/help for future studies.

Some basic facts about Black holes

- A Solution of Einstein eq.➔ BH is best known as a classical object. We know some of quantum properties of bh such as Hawking radiation.
- Classically BH is stable. Nothing can escape from BH
- In 4D, BH is unique. Topology for 4D bh=S^2
- (M, J, Q) specify the hole. (No hair theorem)
- Kerr-Newman solution (4D) is the most general one.
- How a bh forms? Hoop conjecture

Hoop Conjecture

- HC states (Kip Thorne 1972)

  "An imploding object forms a Black Hole when, and only when, a circular hoop with a specific critical circumference could be placed around the object and rotated. The critical circumference is given by 2 times Pi times the black hole radius corresponding to the object's mass (and angular momentum)."
- In short, "Black Hole forms when [C< 2 pi R]" or "big energy is concentrated in small space".
- HC seems true in any space-time dimension(D>2).
- No rigorous proof available yet.

Higher Dimensional Black objects

- Various Solutions with Topology = S(n+2), S2XSn, S2XR found.
- S2XSn=Black Ring
- S2XR =Black String

} Both seem unstable

- Myers-Perry solution=(4+n)Dim. Rotating BH sol.
- For `small' bh (<< compactification radius or curvature radius), Myers-Perry solution provides the best description.

$$r_h(M,J) = \frac{r_S(M)}{(1+a^2)^{1/n+1}}$$

$$\begin{cases} r_S(M)^{1/n+1} = \dfrac{16\pi G_{4+n} M}{(n+2)\Omega_{2+n}} \\ a = \dfrac{(n+2)J}{2M} \end{cases}$$

$$\Omega_{2+n} = \frac{2\pi^{\frac{n+3}{2}}}{\Gamma(\frac{n+3}{2})}$$

Quantum nature of Black Hole

- Quantum Mechanically BH is unstable.
- Anything can come out of BH via Hawking radiation.
- Temperature= Surface Gravity at the event horizon.
- Small, light bhs are hot!! All things will come out if it is `almost planck size' bh which is the hottest one.
- Entropy= Surface Area/4G, small bh will be eventually non-classical object. Then we need to know QG.
- Greybody factor determines the spectrum of Hawking radiation.

$$T = \frac{(n+1)+(n-1)a^2}{4\pi(1+a^2)r_h} \rightarrow \frac{n+1}{4\pi r_h}$$

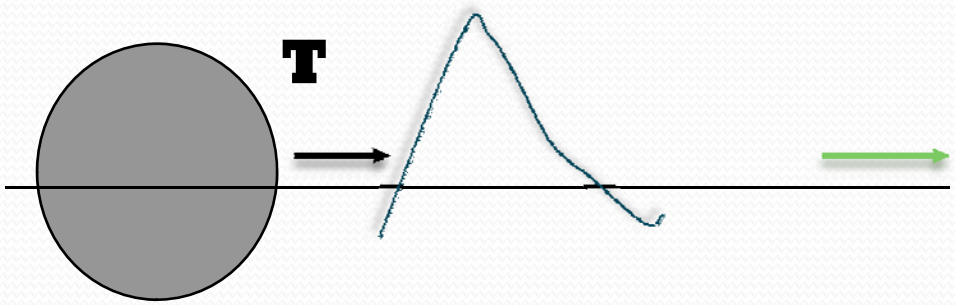
$$S = \frac{M}{(n+2)T}(n+1-\frac{2a^2}{1+a^2}) \rightarrow \frac{\Omega_{2+n} r_h^{2+n}}{4G_{4+n}}$$

Greybody factor

= Absorption Probability of wave mode (s, l, m) by BH.

= Modification factor of the curved geometry

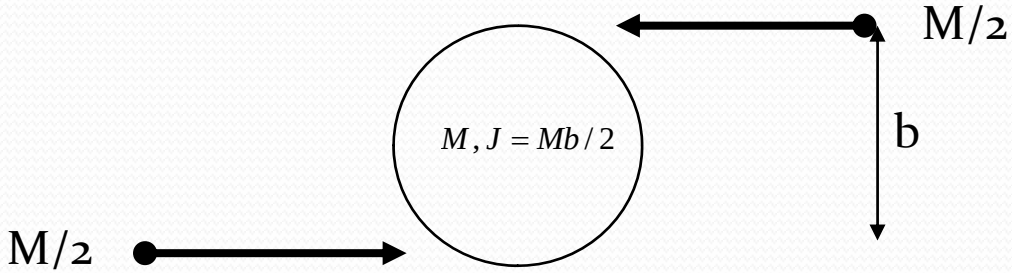
$$-\frac{d}{dt}\begin{pmatrix} M \\ J \end{pmatrix} = \frac{1}{2\pi}\sum_{s,l,m} g_s \int d\omega \frac{\Gamma_{s,l,m}}{e^{\omega - m\Omega/T} \mp 1}\begin{pmatrix} \omega \\ m \end{pmatrix}$$



(NOTE)
4D: 1970s Teukolsky, Page
(4+n)D brane fields: 2003-
Ida-Oda-Park I,II,III
Kanti et.al.
Implemented in BlackMax

Production Cross section estimation

(based on Hoop conjecture, taking angular momentum into account)



$$\Delta = r^2\left(1-(\frac{r_s}{r})^{1+n}+\frac{a^2}{r^2}\right)=0$$

$$r_H(M,J) = r_S(M)(1+a^2)^{-1/n+1}$$

$$r_S(M) = C_n(G_{4+n}M)^{1/n+1}, C_n = O(1)$$

$$M=\frac{(n+2)A_{n+2}}{16\pi G}\mu, \qquad J=\frac{2}{n+2}Ma,$$

Hoop Conjecture: $b < 2r_h(M,J) = 2r_h(M_i, bM_i/2),$

$$\sigma = \pi b_{\max}^2 = 4\left[1+\left(\frac{n+2}{2}\right)^2\right]^{\frac{-2}{n+1}}\pi r_S^2$$

D. Ida, K.-y. Oda, SCP,
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Conventions

- Planck scale (I would take PDG convention)

$$S = \frac{1}{8\pi G_{4+n}} \int d^{4+n}x \frac{R}{2}$$

$$8\pi G_{4+n} = \frac{N_n}{M_D{}^{2+n}} \qquad N_n = (2\pi)^n (PDG), 1(RS), 8\pi(DL), 2(2\pi)^n (GT)..$$

- I would follow the PDG convention

$$r_S(M) = k(n)\left(\frac{M}{M_D}\right)^{\frac{1}{n+1}} \frac{1}{M_D}$$

$$k(n) = \left(\frac{(2\pi)^n}{(n+2)\Omega_{2+n}}\right)^{\frac{1}{n+1}} = 0.46(n=1) - 2.4(n=6)$$

Physical quantities (PDG convention)

$$T(n=1) = 0.34 M_5 \left(\frac{M_5}{M} \right)^{1/2} \qquad S(n=1) = 1.9 \left(\frac{M}{M_5} \right)^{3/2}$$

$$T(n=6) = 0.23 M_{10} \left(\frac{M_{10}}{M} \right)^{1/7} \qquad S(n=6) = 3.8 \left(\frac{M}{M_{10}} \right)^{8/7}$$

$$\sigma(n=1) = \frac{32}{39} \left(\frac{\sqrt{\hat{s}}}{M_5} \right) \frac{1}{{M_5}^2}$$

$$\sigma(n=6) = 33 \left(\frac{\sqrt{\hat{s}}}{M_{10}} \right)^{2/7} \frac{1}{{M_{10}}^2}$$

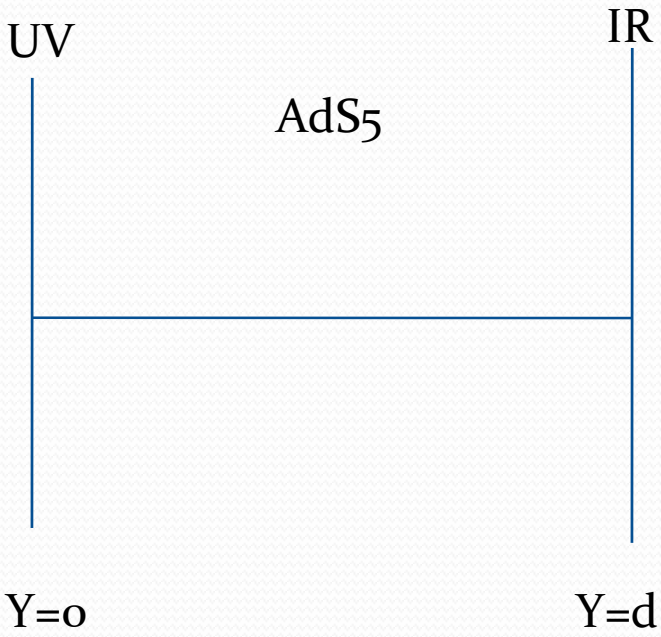
In TeV gravity scenarios

- Such as ADD, RS1
- Gravity becomes `strong' at around 1TeV.
- Black Hole production expected at `Trans-Planckian' collisions (>TeV)
- From now on I would focus on BH production in RS1 (less discussed than ADD)
- considering the SM `off the brane' (less discussed than `on the brane' case)

RS1 $ds^2 = e^{-2y/l} dx^2 - dy^2$

- `scale' is position dependent. $M(y) = e^{-y/l} M$
- UV/IR hierarchy is due to the warping.

$$\frac{M_{IR}}{M_{UV}} = e^{-d/l} \approx 10^{-15}; d \approx 35l$$

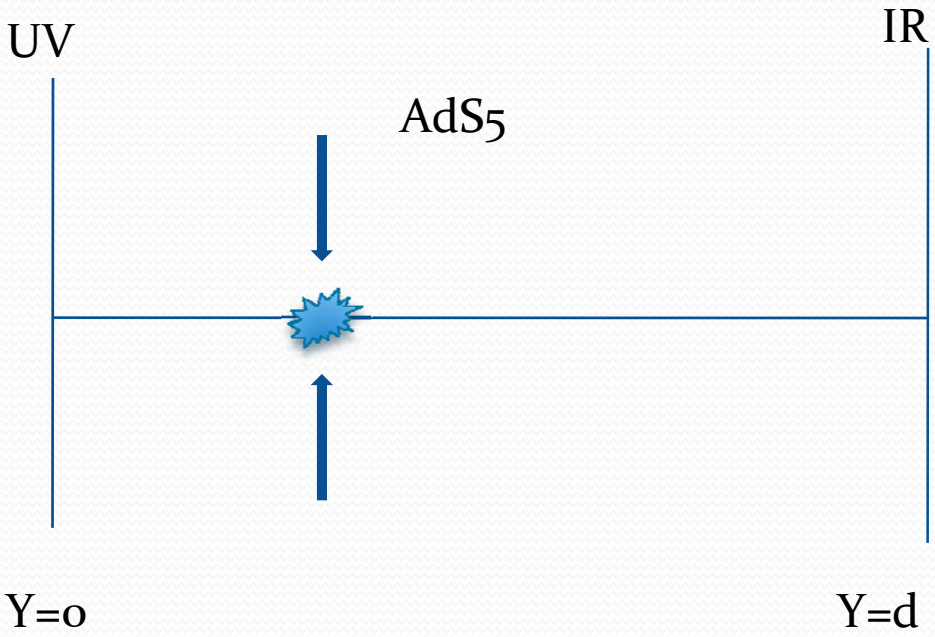


BH production on UV brane

$$\sigma_0 = \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{M^2}$$

We will not see this event since it is Mpl suppressed!

BH production at an arbitrary `y'



$$\sigma(y) = \sigma_0 e^{2y/l} = \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{M^2}e^{2y/l}$$

BH production on IR brane

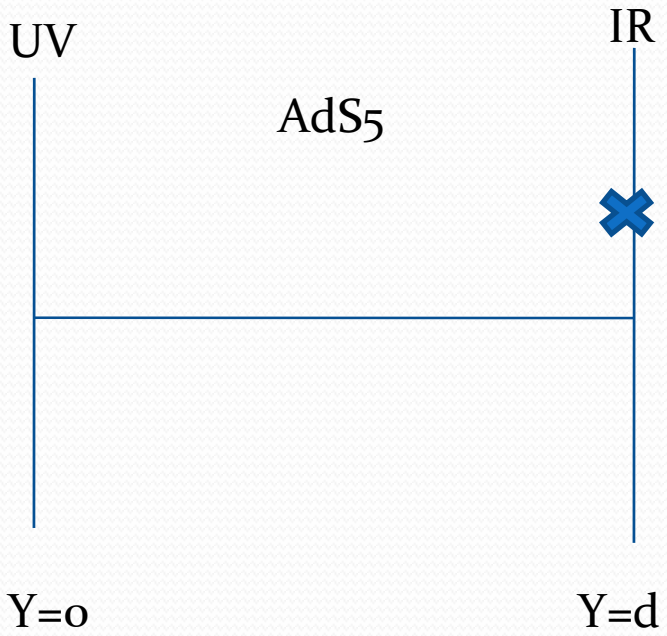
*Note: (E/M) is scale invariant.
*Cross section~1/TeV^2.

$$\sigma_{IR} = \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{M^2}e^{2d/l}$$

$$= \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{\bar{M}^2}$$

RS1-orginal

- All the SM particles lie on the IR brane.
- They `feel' strong gravity at the IR scale.
- BH production rate ~1/TeV²
- The LHC as a BH factory



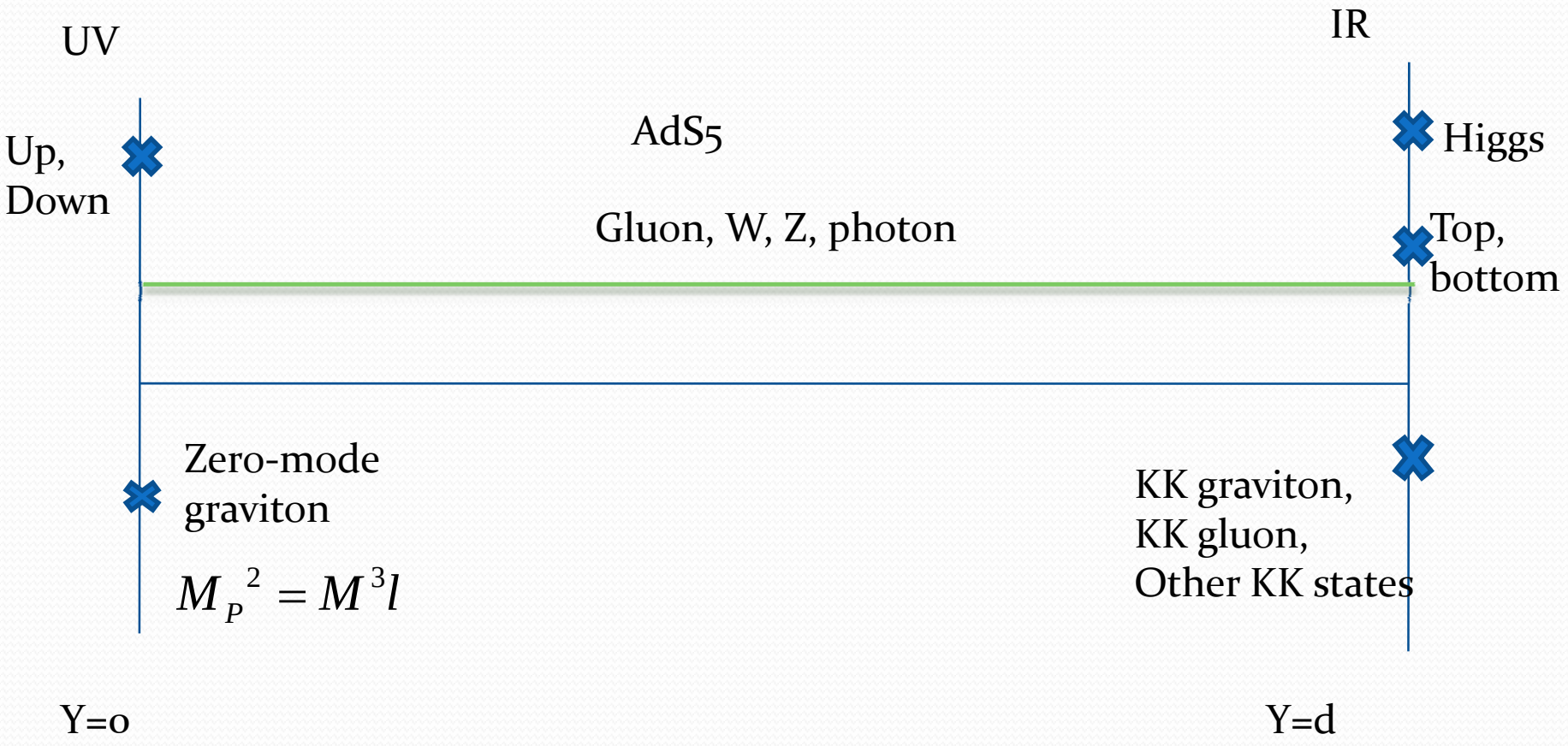
$$\sigma_{IR} = \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{M^2}e^{2d/l}$$

$$= \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{\bar{M}^2}$$

RS1-bulk SM

- To address the hierarchy problem, we would put the Higgs boson on the IR brane (or in the vicinity of the IR brane)
- For flavor problem, longevity of proton, better low energy data fit, etc., we would put 1^{st},2^{nd} generations on the UV brane (or in the vicinity of UV brane).
- 3^{rd} generation (b_R, t_L, t_R) may be on the IR brane. As a bonus, Large Yukawa for the top is also understandable due to the large overlap with the Higgs.
- (Massless, zero-mode) Gauge bosons are `flat' in the bulk.
- (Probably) The most realistic set-up in RS1 models.

Profile: RS1-bulk SM



Gravity scale for the SM particles

- Higgs, top, bottom as well as the longitudinal components of (W, Z) `feel' the TeV gravity.
- The IR-tip of gluon, photon and the transverse components of (W, Z) `feel' the TeV gravity.
- Others (such as 1^{st}, 2^{nd} generation fermions) `feel' the Planck –weak- gravity.

BH production in RS1-bulk

- PP-collider

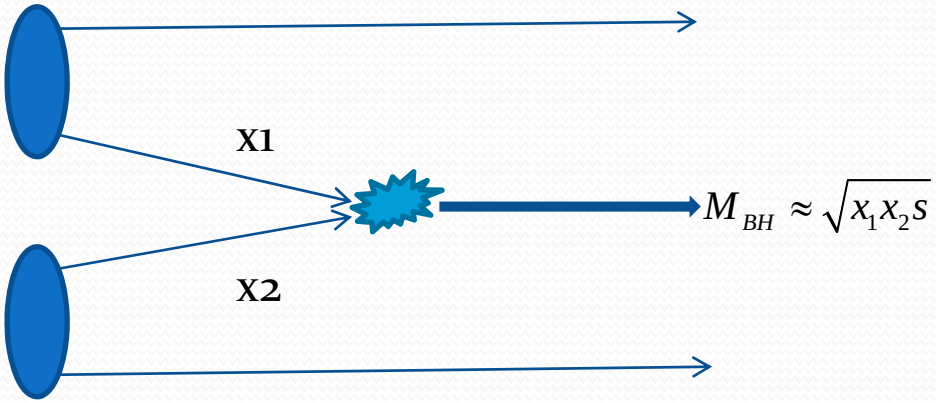
$$\sigma \approx \sigma_{bb+b\bar{b}} + \sigma_{gg} + \sigma_{gb+g\bar{b}} + \sigma_{W_L W_L + Z_L Z_L} + \sigma_{g W_L + g Z_L}$$

- Bottom: small PDF
- Gluon: wave function suppression for each gluon $1/\sqrt{2d/l} \sim 1/\sqrt{70}$
- W_L, Z_L: weak vertex suppression by $\alpha_W / 4\pi$
- Indeed, Thermal black hole production is highly suppressed. (See e.g. Patrick-Lisa's paper)

Closer look: bb+bbbar

$$\sigma_{bb+b\bar{b}}(s) = \int dx_1 \int dx_2 \, f_b(x_1, \sqrt{x_1 x_2 s}) \, f_b(x_2, \sqrt{x_1 x_2 s}) \hat{\sigma}(\sqrt{x_1 x_2 s}) + (b \leftrightarrow \bar{b})$$

$$\hat{\sigma}(\sqrt{\hat{s}}) = \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{\bar{M}^2}$$



Suppressed by PDF!

Closer look: gg

- Only `tip' of the gluon contribute to the bh formation.
- `Bulk' contribution is exponentially suppressed.(negligible)

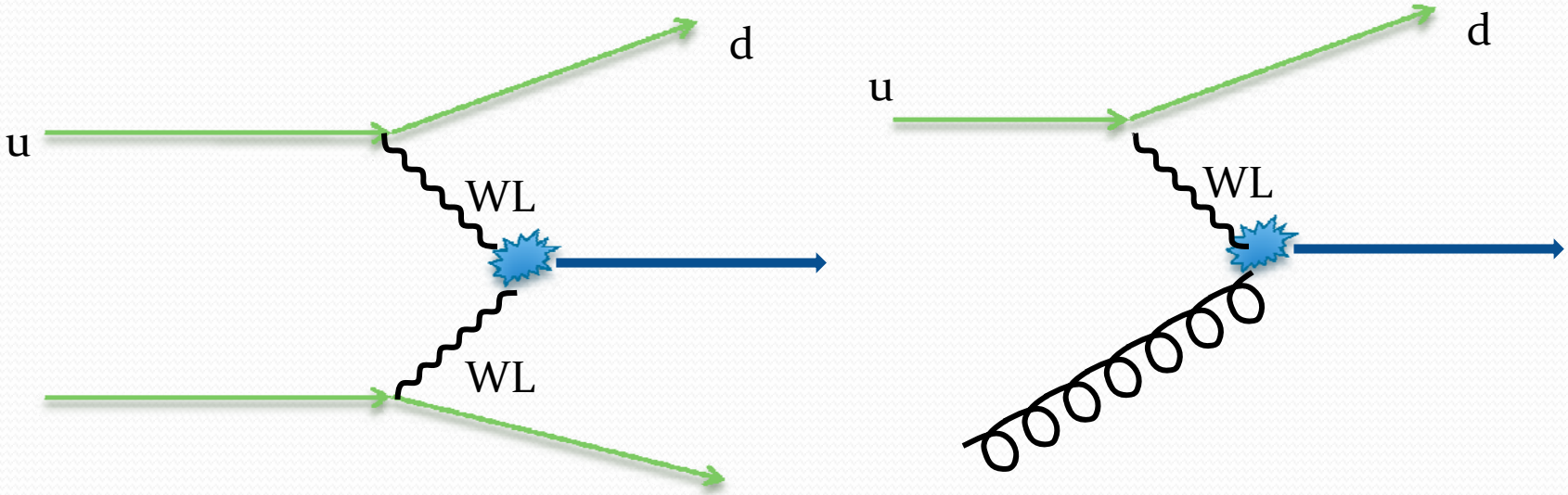
$$\sigma_{gg}(s) = \int dx_1 \int dx_2 \, f_g(x_1, \sqrt{x_1 x_2 s}) \, f_g(x_2, \sqrt{x_1 x_2 s}) \hat{\sigma}(\sqrt{x_1 x_2 s})$$

$$\hat{\sigma}(\sqrt{\hat{s}}) = \frac{32}{39}\left(\frac{\sqrt{\hat{s}}}{M}\right)\frac{1}{\bar{M}^2} \times \left(\frac{1}{\sqrt{2d/l}}\right)^2$$

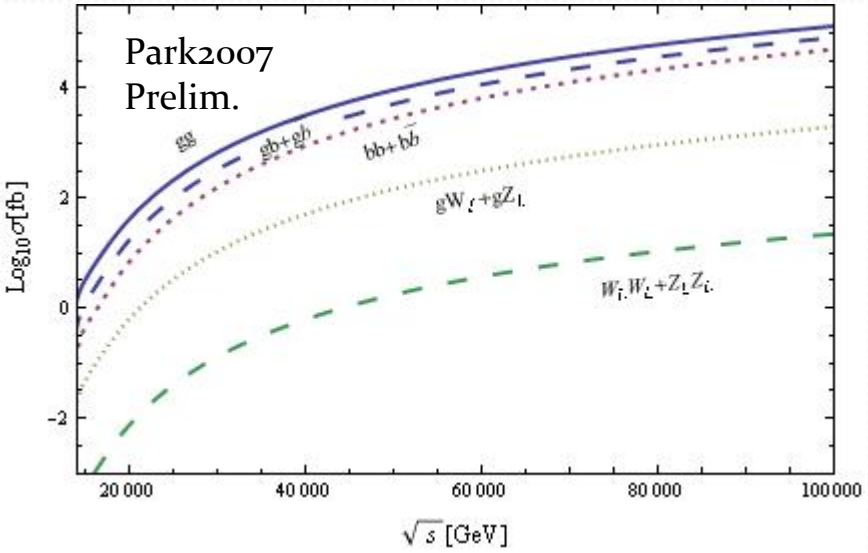
~1/70

Closer look: W_L, Z_L

- By the equivalence theorem, the longitudinal components of the weak gauge bosons are effectively the unphysical Higgs.
- Localized on the IR brane and feel the TeV gravity.
- Suppressed by $\alpha_W / 4\pi$, $(\alpha_W / 4\pi)^2$



Production Cross section



Indeed, Thermal black hole production is highly suppressed.
(See e.g. Patrick-Lisa's paper on `Quantum' black hole production)

However, BH is still interesting!

- Signal is totally different from any others.

Exotic signals expected

- Same-sign leptons: e-e-, e-e-e- …
- Lepton number violation, Baryon number violation
- Black hole does not preserve any ‘global’ quantum number.
- Most probably, we may not need to have huge number of bhs for discovery.

Additional words on Decay channels

- Mainly to the particles on the IR brane thanks to the locality.
- Gluon emission is suppressed by 1/sqrt(70)
- Large number of bjets and top quarks
- Higgs, WL, ZL signals
- Bulk Graviton emission suppressed in RS1. (due to small number of polarization, Z2 symmetry and large warping etc..). This is good for us since they are mostly `missing energy'.

No conclusion.
I just would like to call for your attention/help.

- First of all, Bgrd study required. (e.g. 3j,4j,5j,6j…)

(Steffen, Giacomo, Tomasso suggested 2j+2l,3j+2l..etc would be better channels. Let's see.)

- No known ways of Mass reconstruction, Angular momentum reconstruction etc.
- Seeks for `golden channel' for bh discovery
- Even gen. BlackMax: full greybody factor implemented
- http://www-pnp.physics.ox.ac.uk/~issever/BlackMax/blackmax.html